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14. ABSTRACT

During the period of performance, the major tasks have been to perform correlative studies between low frequency type II bursts representing shock waves and white-light coronal mass ejections (CMEs). The solar sources of all the CMEs associated with the type IT bursts were identified using SOY-TO/FIT and Vohkoh/SXT data. In this process, a complete catalog of all the CMEs observed. by the SOHO mission has been created and provided online to the scientific community ~http://cdaw. gsfc .nasa.gov). This study revealed that long-wavelength radio bursts detected by Wind/WAVES experiment are indicative of a special population of CMEs that are wider and faster than regular CMEs, Further correlative studies were used in improving the empirical CME arrival model to predict the arrival of CMEs at I AU. In the following, a brief description of som.e specific results obtained with. the support of the AFOSR

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FINAL REPORT

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1. Research Objectives

(i) To characterize the large-scale corona using white light, X-ray, EUV and radio data and study the eruptive structures such as coronal mass ejections (CMEs) propagating through it. (ii) To explore the earliest signatures of coronal shocks from EUV and radio data. (iii) To find the relation between coronal and interplanetary shocks using near-Sun and near-Earth observations of solar eruptive events. (iv) To understand the physical processes that lead to the modification of shock and CME speeds as they propagate through the interplanetary medium. (v) To find the relative importance of flares and shocks in producing solar energetic particles.

2. Summary of Accomplishments

During the period of performance, the major tasks have been to perform correlative studies between low frequency type II bursts representing shock waves and white-light coronal mass ejections (CMEs). The solar sources of all the CMEs associated with the type II bursts were identified using SOHO/EIT and Yohkoh/SXT data. In this process, a complete catalog of all the CMEs observed by the SOHO mission has been created and provided online to the scientific community (http://cdaw.gsfc.nasa.gov). This study revealed that long-wavelength radio bursts detected by Wind/WAVES experiment are indicative of a special population of CMEs that are wider and faster than regular CMEs. Further correlative studies were used in improving the empirical CME arrival model to predict the arrival of CMEs at 1 AU. In the following, a brief description of some specific results obtained with the support of the AFOSR grant is provided.

2.1 Interacting CMEs

In the process of studying type II radio bursts from Wind/WAVES, we discovered the phenomenon of CME interaction. During the collision, intense continuum-like radio emission is observed following the interplanetary type II burst. At the time of the radio emission, white light coronagraphic images show a fast CME overtaking a slow CME. We interpret the radio enhancement as a consequence of shock strengthening when the shock ahead of the fast CME plows through the core of the preceding slow CME. The duration of the radio enhancement is consistent with the transit time of the CME-driven

shock through the core of the slow CME. As a consequence of the interaction, the core of the slow CME changed its trajectory significantly. Based on the emission characteristics of the radio enhancement, we estimate the density of the core of the slow CME to be ~4×10^4 cm^-3. The CME interaction has important implications for space weather prediction based on halo CMEs: some of the false alarms could be accounted for by CME interactions. The observed CME interaction could also explain some of the complex ejecta at 1 AU, which have unusual composition. A preliminary survey showed that collision between CMEs is very common in the interplanetary medium. CME-CME, CME-shock and shock-shock interactions are clearly observed in the near-Sun interplanetary medium.

2.2 CME and Sock Arrival Models

The empirical CME arrival model described in Gopalswamy et al. [2000] has been improved (i) by minimizing the projection effects (using data from spacecraft in quadrature) in determining the initial speed of CMEs, and (ii) by allowing for the cessation of the interplanetary acceleration before 1 AU. The resulting effective IP acceleration was higher in magnitude than what was obtained from CME measurements from spacecraft along the Sun-Earth line. We evaluated the predictive capability of the CME arrival model using recent two-point measurements from the Solar and Heliospheric Observatory (SOHO), Wind and ACE spacecraft. We found that an acceleration cessation distance of 0.76 AU is in reasonable agreement with the observations. The new prediction model reduces the average prediction error from 15.4 to 10.7 hrs. The model is in good agreement with the observations for high speed CMEs. For slow CMEs, the model as well as observations show a flat arrival time of ~4.3 days. Use of quadrature observations minimized the projection effects naturally without the need to assume the width of the CMEs. However, there is no simple way of estimating the projection effects based on the surface location of the Earth-directed CMEs observed by a spacecraft (such as SOHO) located along the Sun-Earth line because it is impossible to measure the width of these CMEs. The standard assumption that the CME is a rigid cone may not be correct. In fact, the predicted arrival times have a better agreement with the observed arrival times when no projection correction is applied to the SOHO CME measurements. The results presented in this work suggest that CMEs expand and accelerate near the Sun (inside 0.7 AU) more than our model supposes; these aspects will have to be included in future models. We have developed a lookup table that can be used to predict the arrival of CMEs at 1 AU, once we know its initial speed from white light observations.

The CME arrival was recently extended to predict the 1-AU arrival of IP shocks using the "piston-shock" relationship. The shocks arrived typically about 0.5 day ahead of the CMEs. The standoff distance was smaller for faster CMEs, as expected. We also studied a large number of CMEs and their associated interplanetary (IP) shocks for the period 1996-2002 to assess the influence of preceding CMEs on the propagation of IP shocks. The 1-AU arrival times of the CMEs shocks were obtained from by inputting the initial speed of CMEs into empirical models. It was found that the propagation characteristics of some of the fast CMEs and their shocks are modified by the interaction with the preceding CMEs. Accordingly, the arrival times of IP shocks show deviation from those of the non-interacting CMEs.

2.3 Prominence Eruptions and Coronal Mass Ejections

We performed a statistical study of a large number of solar prominence events (PEs) observed by the Nobeyama Radioheliograph. They studied the association rate, relative timing and spatial correspondence between PEs and CMEs. They classified the PEs as radial and transverse, depending on whether the prominence moved predominantly in the radial or horizontal direction. The radial events were faster and attained a larger height above the solar surface than the transverse events. Out of the 186 events studied, 152 (82%) were radial events, while only 34 (18%) were transverse events. Comparison

with white-light CME data revealed that 134 (72%) PEs were clearly associated with CMEs. They compared their results with those of other studies involving PEs and white light CMEs in order to address the controversy in the rate of association between CMEs and prominence eruptions. They also studied the temporal and spatial relationship between prominence and CME events. The CMEs and PEs seem to start roughly at the same time. There was no solar-cycle dependence of the temporal relationship. The spatial relationship was, however, solar cycle dependent. During the solar minimum, the central position angle of the CMEs had a tendency to be offset closer to the equator as compared to to that of the PE, while no such effect was seen during solar maximum.

2.4 Coronal and Interplanetary Environment of Large Solar Energetic Particle Events

We studied the properties of CMEs associated with large solar energetic particle (SEP) events during 1997-2002 and compared them with those of preceding CMEs from the same source region. The primary findings of this study are (1) High-intensity (> 50 protons/(sqcm.s.sr)) events are more likely to be preceded by other wide CMEs. (2) The preceding CMEs are faster and wider than average CMEs. (3) The primary CMEs often propagate through the near-Sun interplanetary medium severely disturbed and distorted by the preceding CMEs. (4) The occurrence rate of the SEP events, long-wavelength type II bursts and the fast and wide frontside western hemispheric CMEs is quite similar, consistent with the scenario that CME-driven shocks accelerate both protons and electrons; major flares have a much higher rate. (5) The SEP intensity is better correlated with the CME speed than with the X-ray flare class. We also used a specific event to demonstrate that preceding eruption from a nearby source can significantly affect the properties of SEPs and type II radio bursts.

2.5 CMEs Associated with Metric Type II Bursts

We studied the characteristics of CMEs which show temporal association with type II bursts in the metric domain but not in the decameter/hectometric (DH) domain. This study is based on a set of 80 metric (m) type II bursts associated with solar-surface events in the solar western hemisphere. It was found that in general, the distribution of the widths and speeds of the CMEs associated with metric (but not DH) type II bursts are shifted towards higher values compared to those of all CMEs observed by LASCO in the 1996-2001 period. We also found that these distributions have lower values than the same distributions of the CMEs associated with DH type II bursts. In terms of energy, this means that the CMEs associated only with metric type II bursts are more energetic (wider and faster) than regular CMEs but less energetic than the CMEs associated with DH type II bursts. Type II radio bursts at decameter-hectometric (DH) and kilometric wavelengths are indicative of CME-driven shocks in the interplanetary medium. Only a subset of these type II bursts continue from the DH to the km regimes. These long-lasting type II bursts (80%) are also associated with metric Type II bursts. The associated CMEs were found to be the most energetic of all CMEs. There seems to be a hierarchy of CME energies, progressively increasing in association with metric type II bursts, DH type bursts and the long-lasting type II bursts.

2.6 Coronal Streamer Changes and Prominence Eruptions

We investigated white-light coronal streamers as pre-eruption configurations of CMEs. Coronal streamers overlie prominences and often possess all the substructures of CMEs. We studied a set of prominence eruptions associated with streamer changes with no obvious CMEs. The streamer changes and microwave prominence eruptions were observed by the Nobeyama radioheliograph and Solar and Heliospheric Observatory (SOHO), respectively. Multiwavelength data showed that at least one of the streamer events involved heating and small-scale material ejection that subsequently stalled. We compared the properties of the streamer-related events with those of general population of prominence

events. We found that the properties of streamer-related prominence events were closer to those of prominence eruptions with transverse trajectories. We concluded that the partial filament eruptions occur frequently and may serve as the mechanism by which streamers distend before erupting as CMEs.

2.7 Narrow Coronal Mass Ejections

We investigated the statistical properties of narrow coronal mass ejections (CMEs, angular width are < 20 deg) with particular emphasis on comparison with normal CMEs. There were 806 narrow CMEs from the online LASCO/CME catalog (http://cdaw.gsfc.nasa.gov/CME_list). We found that (1) the fraction of narrow CMEs increased from 12% to 22% towards solar maximum, (2) during the solar maximum, the narrow CMEs were generally faster than the normal ones, (3) the maximum speed of narrow CMEs (1141 km/s) was much smaller than that of the normal CMEs (2604 km/s). These results imply that narrow CMEs do not form a subset of normal CMEs and have a different acceleration mechanism from normal CMEs.

2.8 New Method for Measuring the Properties of Halo CMEs

It is well known that coronagraphic observations of halo coronal mass ejections (CMEs) are subject to projection effects. Viewing in the plane of the sky makes it difficult to determine the crucial parameters such as the space speed, width and source location. Assuming that halo CMEs have constant velocities and that they are symmetric and propagate with constant angular widths, we developed a technique which allows to obtain the required parameters. This technique requires measurements of sky-plane speeds and the moments of the first appearance of the halo CMEs above opposite limbs. They applied this technique to obtain the parameters of all the halo CMEs observed by the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO) until the end of 2002. One of the important finding is that the space speed is only 20% larger than the sky-plane speed.

2.9 The CDAW Data Center

The CDAW data center is a repository of information on geoeffective solar events such as coronal mass ejections. This data center maintains a number of specialized data bases such as the Living With a Star (LWS) CDAW data base on solar energetic Particle events and the campaign events for the SHINE 2003 workshop. The data base is open to public and the basic objective is to provide value-added data products from NASA missions to enhance the scientific return. The Solar and Heliospheric Observatory (SOHO) mission's Large Angle and spectrometric coronagraphs (LASCO) have detected more than 7000 CMEs from its launch in 1995 until the middle of 2003. These CMEs are identified, measured and cataloged online and made available to the scientific community (http://cdaw.gsfc.nasa.gov/CME_list).

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1439, 2000.

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17. "Estimation of projection effect of CMEs from the onset time of shock-associated type III radio burst", G. Michalek, N. Gopalswamy, M. J. Reiner, S. Yashiro, M. L. Kaiser, and R. A. Howard, Estimation of projection effect of CMEs from the onset time of shock-associated type III radio burst, in Proc. of the SOHO 11 Symposium on From Solar Min to Max: Half a Solar Cycle with SOHO, 11-15

March 2002, Davos, Switzerland. Edited by A. Wilson, ESA SP-508, Noordwijk: ESA p. 449, 2002.

18. "MHD modeling of CME and CME interactions in a bi-modal solar wind: a preliminary analysis of the 20 January 2001 two CMEs interaction event", S. T. Wu, A. H. Wang, and N. Gopalswamy, MHD modeling of CME and CME interactions in a bi-modal solar wind: a preliminary analysis of the 20 January 2001 two CMEs interaction event", in SOLMAG 2002. Proceedings of the Magnetic Coupling of the Solar Atmosphere Euroconference and IAU Colloquium 188, 11 - 15 June 2002, Santorini, Greece. Ed. H. Sawaya-Lacoste. ESA SP-505, p. 227, 2002.

3.3 Accepted/Submitted for Publication

1. Variability of Solar Eruptions during cycle 23, N. Gopalswamy, S. Nunes, S. Yashiro, and R. A. Howard, Adv. Space Res., in press, 2003

2. Coronal Mass ejection and particle acceleration during the 2001 April 14-15 events, N. Gopalswamy, S. Yashiro, M. L. Kaiser, and R. A. Howard, Adv. Space Res., in press, 2003

3. Properties of Narrow Coronal Mass Ejections Observed with LASCO, S. Yashiro, N. Gopalswamy, G. Michalek, and R. A. Howard, Adv. Space Res., in press, 2003

4. On Coronal Streamer Changes, N. Gopalswamy, M. Shimojo, W. Lu, S. Yashiro, K. Shibasaki, and R. A. Howard, Adv. Space Res., in press, 2003

5. "Coronal Mass Ejection Activity During Solar Cycle 23", N. Gopalswamy, A. Lara, S. Yashiro, S. Nunes, and R. A. Howard, Proceeding of Solar Variability as an input to the Earth's Environment, ESA-SP, in press.

6. "Interplanetary Radio Bursts", N. Gopalswamy, in Solar and Space Weather Radiophysics edited by D. E. Gary and C. O. Keller, Kluwer ASSL Volume, in press, 2003.

7. "An empirical model to predict 1-AU arrival of interplanetary shocks", N. Gopalswamy, A. Lara, S. Yashiro, and R. A. Howard, Adv. Space Res., submitted, 2003

3.4 Invited Lectures, Presentations, Talks, etc.:

1 . "Measurements of 3-D Sunspot Coronal Magnetic Fields From Coordinated SOHO EUV and VLA Radio Observations," Brosius, J. W.,
Landi, E., Cook, J. W., Newmark, J., Gopalswamy, N., Lara, A., AGU 2001, Spring meeting, SH41A-13.

2. "Testing the Empirical CME Arrival Model Using Earth Directed Events," Lara, A., Gopalswamy, N., Dasso, S., Dasso, S., Yashiro, S.,
AGU 2001, Spring meeting, SH61A-05.

3. "Origin and Early Evolution of Coronal Mass Ejections, " Gopalswamy, N, AGU 2001, Spring meeting, SH61A-01 INVITED.

4. "Acceleration and Deceleration of CMEs Associated with Long Wavelength Radio Bursts,"

Gopalswamy, N., Yashiro, S., Kaiser, M. L.,
Howard, R., AGU 2001, Spring meeting, SH31C-07.

5. "LASCO CME Speeds and Metric Type II Radio Bursts," Hammer, D., Gopalswamy, N., Yashiro, S, AGU 2001, Spring meeting, SH22C-01.
6. "Estimation of projection effect of CMEs from onset time of type III radio bursts," Michalek, G., Gopalswamy, N., Reiner, M., Yashiro, S.,
AGU 2001, Spring meeting, SH22A-05.

7. "An Observational Study of Solar Coronal-hole Regions Showing Radio Enhancements," Moran, T. G., Gopalswamy, N., Dammash, I.,
Wilhelm, K., AGU 2001, Spring meeting, SH41A-13.

8. "Development of SOHO/LASCO CME Catalog and Study of CME Trajectories," Yashiro, S., Gopalswamy, N., St. Cyr, O. C., Lawrence, G., Michalek, G., Young, C. A., Plunkett, S. P., Howard, R. A., AGU 2001, Spring meeting, SH31C-10.

9. "CME Cannibalism," Department of Astronomy, University of Maryland, College Park, July 31, 2001.

10. "CME Interaction in the near-Sun interplanetary medium," invited talk, SHINE 2001, ASPEN, Colorado, June, 2001.

11. "CME initiation and detection through dimming and radio signatures," invited talk, SHINE 2001, ASPEN, Colorado, June, 2001.

12. "Origin and Evolution of CMEs" invited talk, IAGA/IASPEI Joint Assembly, Hanoi, Vietnam, August 22, 2001.

13. "Relation between CMEs and ICMEs", invited talk, COSPAR Colloquium, Beijing, China, September 12, 2001.

14. "Recent results from the Wind/WAVES experiment", invited talk, NOAA's Geostorms Workshop, Boulder, Colorado, Oct 29-Nov 1, 2002.

15. "Complexity of Solar Eruptions", invited talk, SHINE 2002, Banff, Canada, Aug 18-22, 2002.

16. "Coordinated Data Analysis Workshops", invited talk, EGS/AGU/EUG Joint Assembly, Nice, France, April 7-11, 2003.

17. "Shocks, CMEs and Plasmoids", invited talk, SIRA workshop, May 13, 2003, Lanham, MD.

18. "Radio observations of coronal mass ejections", invited talk, Green Bank Workshop on "Solar Radiophysics with the Frequency Agile Solar Radiotelescope" (May 23-25), 2002.

19. "Interplanetary radio bursts", invited talk, The American Astronomical Society (AAS), 200th Meeting, Albuquerque, NM, June 2 - 6 2002.

20. "Evidence for magnetic structure in CMEs from coronal observations", invited talk, The American Astronomical Society (AAS), 200th Meeting, Albuquerque, NM, June 2 - 6 2002.

3.5 Professional Activities (editorships, conference and society committees, etc.):

1. Member, Organizing Committee of International Astronomical Union's Commission 10 (1997-2005)

2. Convener, IAGA Division IV Symposium G4.03, The Active Sun, July 2001.
3. Co-convener, Special Session on CME Theory and Observations, AGU Spring meeting, Boston, 2001.

4. Team Leader, Pre-CME Sun, 2000-2004, International workshop on CMEs, International Space Studies Institute, Germany.

5. Steering Committee member, Solar Heliospheric and Interplanetary Environment (SHINE) group (2001-2004).

6. Member, Scientific Organizing Committee, 1st STEREO Workshop, Paris, France, March 2002.

7. Convener, Special Session on interacting CMEs, Fall AGU 2001, San Francisco, CA.

8. Chair, Scientific Organizing Committee, Living With a Star (LWS) Coordinated Data Analysis Workshop (CDAW) on Solar Energetic Particles, July 23-26, 2002.

9. Convener, Chapman Conference on Solar Energetic Plasmas and Particles, Turku, Finland, Aug 2-6, 2004.

10. Convener, EGS special session on International Heliophysical Year, Nice, France, April 2003.

11. Chair, Scientific Organizing Committee, Solar Imaging Radio Array (SIRA) Workshop, May 13-14, 2003, Lanham, MD.

12. Associated Editor, JGR Space Physics, 2001-2005.

4. Technology Transitions/Transfers:
Detailed Listing have already been submitted in April 2003 (see appendix).

SUMMARY FACT SHEET

EMPIRICAL SHOCK ARRIVAL MODEL/J. BROSIUS

SUMMARY:

Coronal mass ejections (CMEs) from the Sun constitute one of the primary causes of geomagnetic storms. CMEs also drive shocks, which in turn accelerate solar energetic particles that pose radiation hazard for technological systems in space. With support from AFOSR, researchers from the Catholic University had developed an empirical CME arrival (ECA) model that takes as input the CME speed from coronagraph observations and outputs the arrival time of CMEs at 1 AU. This model has recently been extended to predict the arrival time of shocks. This empirical shock arrival model (ESA) makes use of the well-known piston-shock relationship.

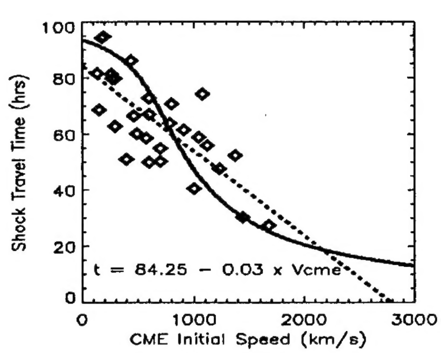
WHAT WAS ACCOMPLISHED:

The AFOSR funded research has resulted in the ESA model, which predicts the arrival time of interplanetary shocks at Earth based on the remote-sensing observations of CMEs by coronagraphs such as the Large Angle and Spectrometric Coronagraph (LASCO) on board the SOHO mission. The input to the model is the sky plane speed measured from coronagraph images of CMEs. An important step in the model is to show that the interplanetary shocks behave like gas-dynamic shocks for a large number of shocks of solar cycle 23. This means the shock arrival can be predicted from CME arrival because there is a definite relation between a CME and its shock (both positions and speeds are related). The following look-up table summarizes the accomplishment of the ESA model: Once the CME speed is measured, the sock travel time from Sun to Earth can be obtained from the Table.

SPEED (KM/S)	TRAVEL TIME (HR)	SPEED (KM/S)	TRAVEL TIME (HR)	SPEED (KM/S)	TRAVEL TIME (HR)
100	92.2	1100	42.3	2100	19.4
200	90.5	1200	38.0	2200	18.3
300	88.2	1300	34.4	2300	17.4
400	85.1	1400	31.4	2400	16.6
500	80.9	1500	28.9	2500	15.8
600	75.2	1600	26.7	2600	15.1
700	68.2	1700	24.8	2700	14.5
800	60.7	1800	23.2	2800	13.9
900	53.6	1900	21.8	2900	13.4
1000	47.5	2000	20.5	3000	12.9

WHY IT IS IMPORTANT:

The ESA model is capable of providing 1-3 day advance warning of the impending arrival of CME-driven shocks at Earth. This is a very useful lead-time for space weather applications.



The empirical shock arrival model (solid curve) developed by the Catholic University allows for 1-3 day advance warning on the arrival of interplanetary shocks at Earth. A straight-line relationship between travel time and CME speed is also given. The data points are actual measurements.